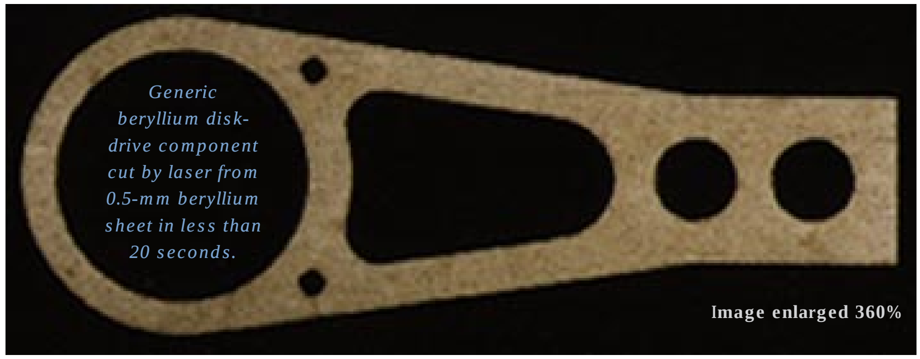
Laser Fabrication of Beryllium Components



Generic beryllium disk-drive component cut by laser from 0.5-mm beryllium sheet in less than 20 seconds.

HISTORICALLY, beryllium metal has been used chiefly for a relatively small number of parts in weapons and guidance systems and in a very few commercial applications. Beryllium's benefits more than offset the high cost and difficulty of fabricating parts; in fact, beryllium components often represent only a small portion of the total cost of the systems in which the components were used. Several new applications, involving small parts and high production rates, show that beryllium metal and alloys would clearly be the superior materials were it not for fabrication costs. Beryllium and beryllium alloys have several properties—low density, high modulus of elasticity, high mechanical damping capacity, and high-frequency resonance—that make them ideal for applications involving sheet product such as computer memory devices. Use of beryllium in drive arms and disk storage would allow more compact designs, leading to smaller, lighter disk drives and increased storage capacity.

Problems and Solutions

Even when great care is used, conventional machining can damage these hard, low-ductility materials, significantly impairing their mechanical performance. Moreover, there is no nondestructive method of detecting such machining damage. Competing materials can be stamped out of sheet product at a high rate, but to date beryllium cannot be stamped with any degree of commercial success.

Welding this low-ductility metal also presents problems. Conventional welding processes require use of a filler metal, that is, a different alloy from the metal being welded. Use of a filler is not desirable for some applications, but autogenous welding—welding without a filler—has been nearly impossible with beryllium.

Researchers at LLNL have found laser alternatives to the conventional methods of cutting and welding beryllium. We have been working with Brush Wellman Inc. (Elmore, Ohio), the only basic supplier of beryllium outside the former Soviet Union, on commercial applications and are using prototype parts. We demonstrated that lasers provide a high-speed, low-cost method of cutting beryllium metal, beryllium alloys, and beryllium/ beryllium oxide composites. In a separate project with Nuclear Metals Inc. (Concord, Massachusetts) and Space Power Inc. (San Jose, California), we developed laser welding processes for commercial structural grades of beryllium that require no filler.

Laser Cutting

For unique LLNL applications, we succeeded in cutting thin, high-purity beryllium foil long ago. Although laser cutting of structural sheet material containing significant amounts of beryllium oxide and impurities had never been tried, we proposed that lasers be used to cut commercial structural grades of beryllium sheet and, further, lasers might do so faster than conventional methods. Of several lasers at LLNL approved for use with beryllium, we chose two for our initial study: a 400-W pulsed YAG (yttrium-aluminum-garnet) laser and a 1000-W continuous-wave carbon dioxide (CO_2) laser. In fact, our attempts were highly successful.

Both lasers easily produced acceptable surface finishes of the cut edges of beryllium parts. The alloy AlBeMet (from Brush Wellman Inc.) and beryllium/beryllium oxide composite sheet material were cut at thicknesses from 0.5 mm (0.020 in.) up to approximately 2.0 mm. The 0.5-mm sheet was cut at speeds up to 2.54 m/min., and thicknesses of 1.8 to 2.0 mm were cut at speeds of 0.5 to 0.8 m/min. The photo above shows a typical generic prototype part cut from a large, 0.5-mm-thick beryllium sheet. The part's outline and six holes were cut in 18 s. Most of this time was spent on relocating the part for cutting, rather than the cutting itself. On a microscopic scale, the cut edges were acceptable, and the part easily met tolerance requirements. In laser cutting, beam size determines the minimum radius possible, which is in the range of 25 μm for our equipment. The smallest holes in the part shown have 1.0-mm radii.

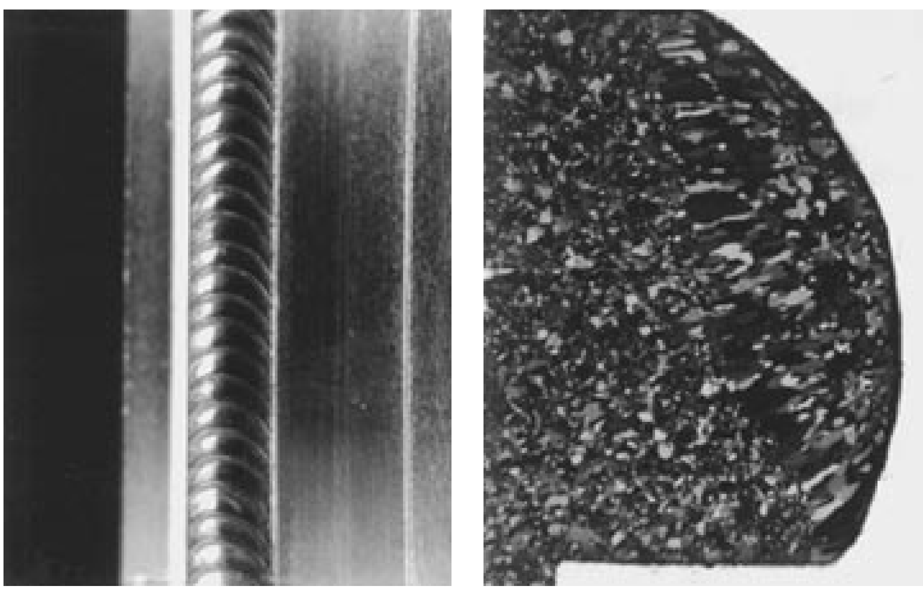
Laser cutting presents other benefits as well. First, the cut width created by material removal (the kerf) is narrow. Thus, the parts can be laid out very efficiently to yield more parts per sheet, and just as important, there is less beryllium waste for disposal. Second, there is no machining damage, as we determined by microscopic examination. We further confirmed this by cutting tensile specimens from the same structural beryllium sheet, and, with no further treatment after laser cutting, pulled them to failure. The mechanical properties (specifically, elongation to failure and ultimate strength) easily met and exceeded specifications. Third, for large-scale production, a more powerful laser could be used and the beam split to cut several parts from a sheet at the same time. Fourth, a laser beam might be piped into a single designated room for beryllium cutting operations, reducing both the number of beryllium workers and the possible exposure of personnel to beryllium particulate.

Autogenous Laser Welding

Where possible, autogenous welding of metals is usually preferred to welding with fillers. Autogenous welding is a simpler process and results in a more homogenous junction of the two pieces being welded. In addition, operating temperatures may militate against the use of filler metal with a lower melting point. However, many metals and alloys do not lend themselves to autogenous welding, which is basically a complicated high-speed casting process.

Low-strength, ingot-grade beryllium has been welded autogenously for more than 30 years. For specialized applications that gave the welding metallurgist freedom in designing the weld, we have autogenously welded thin sheets of ingot beryllium with a laser. We also once autogenously welded structural beryllium using an electron beam. However, the more useful high-strength structural beryllium grades (powder-origin) have not been amenable to autogenous welding without severe cracking.

Several times over the past few years, we have been asked to make or design various specialized beryllium parts for satellites. Whether used for detecting signals from deep space or operating the satellite, these parts could have no foreign material—no filler material in the form of a weld or braze alloy. In the past, we successfully finessed the requirement by making very thin braze joints, usually with aluminum or an aluminum alloy. Recently, however, an application came to our attention in which even a thin braze line with a minimum of filler was not satisfactory.



Autogenous laser weld in commercial structural beryllium. (Left) View of weld bead 25.4 μm in diameter. (Right) Metallurgical cross section of a fusion zone (original magnification 100 ¥).

Through Nuclear Metals Inc., we learned that Space Power Inc. (SPI) needed beryllium caps joined to beryllium cylinders to encapsulate a nontoxic hydride. The cylinder would eventually be a component in a power source for a satellite, and the beryllium had to be the higher-strength structural grade. There were two reasons that the weld had to be autogenous. First, an element of higher atomic weight would harm the performance of the unit. Second, the cylinder operating temperature was more than 600°C, which is above the melting temperature of virtually all welding filler alloys for beryllium. Any filler metal would violate one or both of these requirements. Researchers at a commercial U.S. firm attempted to weld the cylinders using electron-beam-welding procedures but produced severe cracking. SPI obtained welded beryllium cylinders from Russia, but they leaked at temperatures above about 500°C.

With our experience, albeit very limited, in autogenously welding beryllium, we offered to try laser welding the components. The cylinder was to contain an inert cover gas. Laser welding would serve well here, because the cylinder could be placed in a sealed chamber containing the gas and the cap welded to the cylinder by a laser beam passing through a glass port. For the development tests, the cover gas was not required, so we did not use the technique. We knew autogenous welding would be difficult because the required circumferential weld results in substantial residual stress, to which beryllium is not amenable. After considerable experimentation to determine the exact weld design and laser parameters, we succeeded in autogenously welding the cap on the 25.4-mm-diameter cylindrical component. Because of our experience in laser cutting, we preferred the pulsed YAG laser for our welding experiments, but the continuous wave CO_2 laser has promise, as well. The left-hand photo on page 20 shows what a typical laser-weld fusion zone looks like; each individual ridge reflects the individual laser pulse. The right-hand photo shows some columnar epitaxial grain growth in the fusion zone. This growth is not desirable, but refining the welding parameters and slightly modifying the weld design should improve the microstructure.

The sealed cylinder containing the hydride was delivered to SPI, where it is providing excellent results with no leaking above 600°C. This is the first successful application of autogenous laser welding of structural grades of beryllium.

Summary

Beryllium metal, beryllium alloy sheet, and beryllium/beryllium oxide composite sheets are all superior materials for use in various advanced technological applications, such as for improving computer speed and memory capacities. However, conventional machining techniques of these materials impose costs that make their use in commercial applications uneconomical. We have demonstrated that lasers can remove this economic barrier. Lasers can cut components to size at high speeds, with high tolerances and small radii without introducing machining damage, thus yielding high material efficiencies.

We have also shown that lasers allow beryllium to be used in applications requiring autogenous welding. We have autogenously welded commercial structural grades of beryllium.

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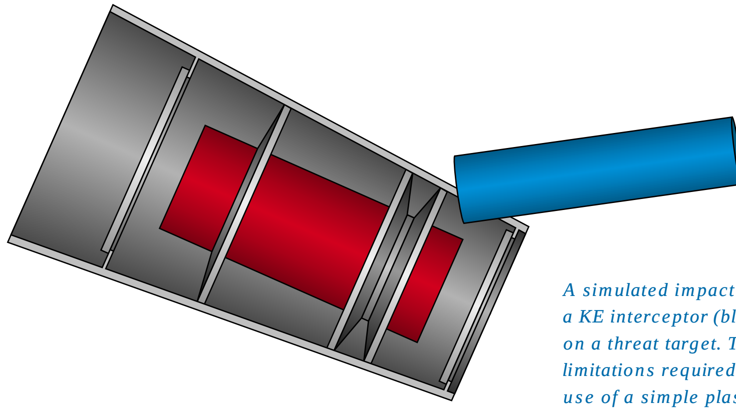
The Kinetic Energy Interceptor: Shooting a Bullet with a Bullet



A simulated impact of a KE interceptor (blue) on a threat target. Test limitations required the use of a simple plastic cylinder to model the interceptor.

ALTHOUGH the Cold War has ended, the threat of proliferation with chemical, biological, and nuclear warheads continues. Two factors further increase the threat from these weapons of mass destruction: knowledge of missile technology has spread extensively, and, in recent years, many countries—some of them unfriendly to the U.S. and its allies—have obtained short- and intermediate-range missiles. The threat posed by such missiles was amply demonstrated during the Gulf War. Thus, the need to protect U.S. and allied forces from these weapons has never been greater.

When nuclear-tipped defensive missiles, such as Sprint and Spartan, were phased out years ago, the U.S. turned for its defense to kinetic-energy "kill" interceptors—missiles that destroy an enemy missile by striking it with lethal force and accuracy at some point in its trajectory. The Patriot missile is probably the best-known kinetic-energy (KE) interceptor in the U.S. defensive arsenal. The Patriot, however, is a short-range interceptor. With continuing threats from various sources, the U.S. is also developing long-range KE interceptors.

To counter the spreading threat of proliferation, LLNL and other laboratories have been participating in a joint program funded by the Ballistic Missile Defense Organization (BMDO), within the Department of Defense, to develop defensive missile systems. Participants are designing, testing, and certifying KE interceptors to defend against current and future missile threats.

The Joint Lethality Working Group

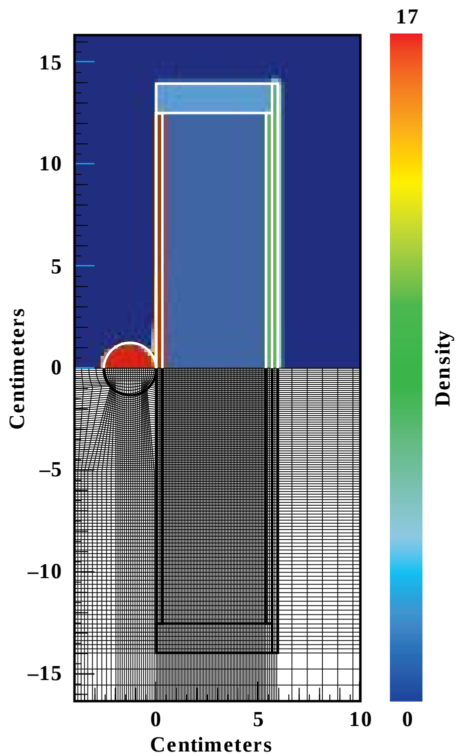
The main criterion for a kinetic-energy interceptor is its lethality—its ability to destroy a threat missile without harm to the threat's target and with no collateral harm. (The destructive coupling of the defensive interceptor's kinetic energy into the incoming nuclear warhead has been likened to shooting a bullet with a bullet.) Within the BMDO program, the Joint Lethality Working Group focuses on the issues related to lethality. In addition to LLNL, the working group includes among its participants the U.S. Army, Air Force, Defense Nuclear Agency, Los Alamos National Laboratory, Sandia National Laboratories, and various government contractors.

The Joint Lethality Working Group is pursuing a program that combines experimentation with computer simulation and code development. Its goal is to design interceptors that are lethal to warheads that exist in present enemy or proliferant nations' stockpiles or are likely to be developed. Working group participants collaborate on the design of each experiment or series of experiments. They devise an interceptor design, a threat warhead design to test it against, and the particulars of the test—for example, relative velocities of the threat and interceptor at impact, location of impact on the threat, and angle of impact.

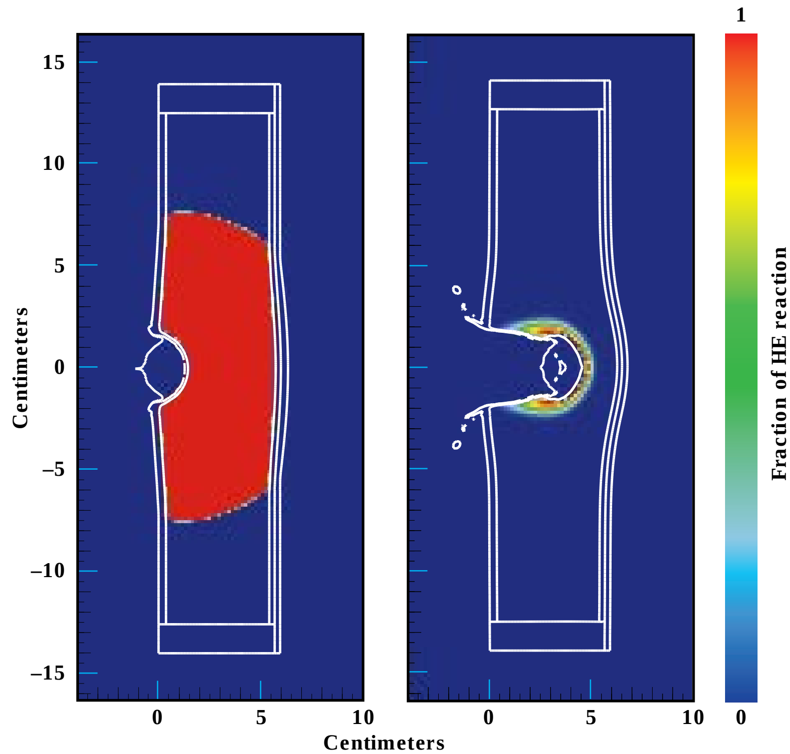
The Interceptor Test Program

While participants collaborate on test design, each separate participant assumes particular responsibilities. LLNL has several tasks within the group. Our chief tasks are to design, fabricate, test, and evaluate models of the nuclear warheads that intelligence reports indicate are within the technological capabilities of various foreign powers—those designs that U.S. interceptors might someday need to destroy in combat. In addition to designing targets, LLNL participates in establishing and defining the experiments in which interceptors are tested against targets. The challenge is to choose experimental parameters, such as projectile weight, closing speed, direction, and angle of incidence that will maximize the return of useful experimental data. To do that, we perform pretest code calculations to establish a test matrix to decide what we will do in a test and determine what results to expect. Then our post-test calculations give us the fidelity of our modeling. This computer-intensive approach to experiment design is a legacy of our practice in underground nuclear tests and helps to ensure a good return on the dollars spent in these experiments.

Test warheads contain no actual nuclear materials, but in other important respects warheads and projectiles alike



Top of figure shows the initial configuration of a 25-mm tungsten sphere impacting the HE target. Colors indicate different material densities. Below is the CALE geometry setup for numerical analysis showing typical zoning used and the material boundaries.



(Left) Prompt detonation of the HE is shown by the fraction of HE reacted after 18 μs for the projectile velocity of 1.3 km/s. Red color indicates fully reacted HE, while blues indicate no reaction. (Right) Low-level reaction in the HE is shown by the small amount of material reacted (essentially no red region), for a projectile velocity of only 1.06 km/s.

are designed to accurately represent real-world systems. This is true whether the models are full scale or are scaled down, as is often the case, because the projectiles must be small enough to be fired by a light gas gun. The models have mock components made of materials that replicate (within their scale) the weight, strength, and other properties of materials in actual warheads and in prospective interceptor designs. The models therefore have the same total or scaled weight and distribution of weight as their counterparts. The figure on the opposite page shows a simulation of a KE interceptor striking a nuclear-tipped tactical missile.

The responses of the materials used in our tests vary greatly over the range of test velocities. The relative velocity (or closing rate) of a KE intercept may vary from a low of 1 to 2 km/s up to a hypervelocity of 8 to 10 km/s (10 km/s = 36,000 km/hr).

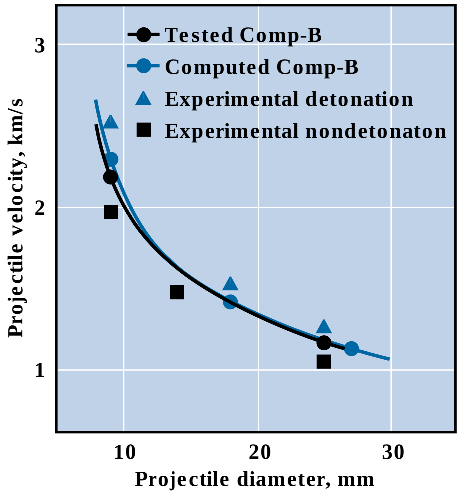
Proving Our Codes

Because only a finite number of tests can be conducted, they must serve dual purposes. They give the experimental results of striking a given target with a given projectile and also provide data with which to refine our codes. As these codes become progressively more refined, they more reliably describe the impacts of simulated projectiles on simulated targets (see above figures). Eventually, the codes should enable us to "test" (within the computer) any combination of warhead and interceptor designs in simulated conditions of the group's choosing. Actual experiments will simply confirm the reliability of the codes.

We are evaluating two lethal mechanisms for killing nuclear warheads: destruction of the high explosives in the warhead, and breakup of the warhead into many fragments.

Both methods eliminate the possibility of nuclear yield, the first by eliminating the trigger for nuclear ignition, the second by eliminating the requisite critical mass for a chain reaction even in the presence of an explosion—as long as the warhead's contact (or salvage) fuze is not armed. Otherwise, the impact of the kinetic energy interceptor is likely to trigger a full-yield nuclear explosion. Only a nuclear interceptor with a yield of a small fraction of a kiloton is sufficient to defeat a fuzed and armed nuclear target.

Actual experiments (figures above) conducted with identical parameters to such simulations are conducted at various two-stage light gas gun facilities. The test results,



Comparison of the CALE calculations for the Composition-B HE initiation with the results of experiments at the Naval Research Laboratory, showing the range between detonation and nondetonation. The calculations show excellent agreement with the test results. Calculated Composition-B density was 1.7 g/cm³; tested density was 1.63 g/cm³.

together with 2D and 3D hydrodynamic code analyses, are used to interpret the tests and establish the lethality of the KE interceptor. One of the codes used extensively for analyses of the intercepts is CALE (an Arbitrary Lagrangian Eulerian code written in the language C), which implements our ignition and growth reactive flow model.[1] CALE enables us to calculate how most types of high explosive (HE) of interest for application in counterproliferation respond when impacted by a KE projectile of given properties. The mesh in the figure on top left of page 23 shows the CALE setup geometry for numerical analysis of a projectile impacting an HE target and the density of a 25-mm tungsten spherical projectile impacting the HE target. The HE figure shows the results of impacts at two relative velocities: at 1.3 km/s, the impact produces a prompt detonation at 15 μs in the HE; at 1.06 km/s, the projectile penetrates into the HE, but at 60 μs has only produced a low-level reaction. The graph (at left) shows a comparison of our analysis with experimental results for Composition-B HE, our benchmark HE used in studies of our ignition growth model. Simulations run on our 2D and 3D codes have shown excellent agreement with experimental results, giving us confidence in their ability to reliably expand the range of test parameters.

Projected Work

For the purpose of studying the effectiveness of warhead interceptors, we have simulated a simple nuclear warhead concept that we believe represents what aggressively proliferant nations might devise. We have built a generic model target for lethality testing and conducted two half-scale tests. We are now building full-scale targets for testing on a sled track at Holliman Air Force Base in New Mexico, where an actual interceptor vehicle will be fired into a target. We will evaluate the lethality of the systems being fielded against this target.

References

1. E. L. Lee and C. M. Tarver, "Phenomenological Model of Shock Initiation in Heterogeneous Explosives," *Phys. Fluids* **23** (12), December 1980, pp. 2362–2372.

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